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## X-RAY SPECTRA OF HERCULES X-1 II. INTRINSIC BEAM

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S. H. PRAVDO  
E. A. BOLDT  
S. S. HOLT  
P. J. SERLEMITSOS



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# X-ray Spectra of Hercules X-1

## II. Intrinsic Beam

S. H. Pravdo<sup>\*</sup>, E. A. Boldt, S. S. Holt,  
and P. J. Serlemitsos

Laboratory for High Energy Astrophysics  
NASA/Goddard Space Flight Center  
Greenbelt, Maryland 20771

### ABSTRACT

The X-ray spectrum of Hercules X-1 was observed in the energy range 2-24 keV with sufficient temporal resolution to allow detailed study of spectral correlations with 1.24 sec pulse phase. A region of spectral hardening which extends over  $\sim 1/10$  pulse phase may be associated with the underlying beam. The pulse shape stability and its asymmetry relative to this intrinsic beam are discussed.

### I. INTRODUCTION

The existence of regular 1.24 second pulsations from Her X-1 is the most convincing evidence that it is a neutron star. A beaming mechanism is required to explain the deeply modulated pulse shapes which are observed (Lamb et al. 1973, Basko and Sunyaev 1975). Many proposed mechanisms obtain their beaming

<sup>\*</sup>Also Dept. of Physics and Astronomy, Univ. of Maryland

directionality from some aspect of the interaction between the accreting matter or emergent X-rays and the magnetic field lines. Each of the models predicts or implies spectral changes which should occur with pulse phase. The spectral changes to be searched for include spectral softening or hardening with decreasing angular beam extent, increased photoelectric absorption, or Comptonization (cf. Illarionov and Sunyaev 1972) of a source spectrum.

The Goddard Space Flight Center Cosmic X-ray spectroscopy experiment (CXS) on board OSO-8 observed Her X-1 with sufficient temporal resolution to examine spectral changes with 1.2 second pulse phase. In this paper we present the results of this observation and discuss their impact on the various models for pulse formation. We suggest a hybrid model which contains both a beaming mechanism due to magnetic fields and an intensity modulation due to the intervening Compton scatterer.

## II. EXPERIMENT AND ANALYSIS

The CXS observed Her X-1 from August 26 to September 3, 1975. Results of this observation concerning spectra observed near a  $\sim$  35-day cycle X-ray turn-on (Becker et al. 1976b) and "iron band" emission (Pravdo et al. 1977) have previously been reported. This detector was a pointed argon-filled proportional counter with an energy range of 2-24 keV, an effective area of  $36.7 \text{ cm}^2$ , and a circular collimated field of view with FWHM of  $3.34^\circ$  (Becker et al. 1976a). Spectral data were obtained

with 20 msec temporal resolution for pulse-height-analyzed counts for a period of two binary orbits. PHA counts from each binary orbit were separately folded modulo the pulsar period determined by this observation (Becker *et al.* 1976b). The reference time of zero pulse phase is August 31.0, 1975 UT. Photon arrival times were corrected for the effects of the Her X-1 binary orbit, satellite orbit, and the Earth's motion.

### III. RESULTS

Figure 1a shows the energy integrated light curve for high state data during one binary orbit folded over the pulsar period of  $1.2378065 \pm 0.0000001$  seconds. It shows a double-peaked pulse, with a dominant first peak, and an intensity minimum following the second peak. This pulse shape is similar to those observed by Doxsey *et al.* (1973) and Holt *et al.* (1974). If these data are divided into smaller time intervals ( $\sim 5$  hr, 30 min, 10 min) the resultant pulses show no significant departures from this shape (Pravdo 1976). Other investigators have suggested the existence in their data of a small additional pulse in the flattened region away from the major double-peaked pulse. It is clear from the present data that a stable minimum region directly follows the major pulse. The succeeding flattened portion of the light curve is a relative maximum. If another pulse does in fact exist in this region, it is small relative to the main pulse and the emission there is dominated by the off-pulse component (i.e. that component immediately prior to the main pulse).

There are spectral changes, sometimes dramatic, with pulse phase. Generally, the pulse shape is seen from 2 to  $\sim$  30 keV. The first peak becomes noticeably narrower at higher energy. Also, the intensity rise is slower than that at lower energies and the peak occurs at a later phase, as reported by Holt et al. (1974). Figure 1b,c shows the results of an automatic spectral fitting program which was applied to the 62 temporal bins each of which contains  $\geq$  4000 total counts. The simple model chosen for this procedure was a power law with absorption and a narrow line at 6.7 keV. Although there is scatter in the histograms, there is one clear trend. In the second half of the first peak the spectrum hardens and "absorption" disappears. The region in which this spectral change occurs is well determined by the "absorption" measure, and was found to occur in the other data set also, but one fold bin later. This implied an error of 0.0000002 sec in the original period determination, if the spectral change actually occurred at the same phase. This was used to suggest a more accurate period.

The spectral hardening which begins midway through the first peak consists of an increase in photon flux with energy  $\gtrsim$  7 keV. Figure 2 shows a superposition of two spectra, one from a single temporal bin within the hardened region and the other from a bin in the interpeak region. This significant spectral change corresponds to about a factor of two increase in the high energy photon flux. If a similar analysis is

performed with spectra from the second peak, no spectral variation is seen. Thus there is a spectral asymmetry as well as an intensity asymmetry between the two peaks.

Spectra obtained during intensity dips are grossly different from the high state spectrum (cf. Becker *et al.* 1976b). However both the pulse and the relative spectral changes with pulse phase remain. In particular the spectral change in the first peak is seen throughout the dips.

#### IV. DISCUSSION

The persistence of the pulse shape is an important fact. A similar shape has been observed since the source discovery (Giacconi 1975). Therefore, the mechanism of pulse formation must be very stable.

The underlying continua are very similar across the entire pulse except for a region of spectral hardening which begins midway through the first peak within 0.02 phase and persists for 0.08 phase ( $\sim 30^\circ$ ). The photon intensity does not change when this spectral change occurs. This appears to rule out scattering processes (Comptonization) if the pulsed emission is truly beamed. Any gross spectral change would be caused by substantial optical depth which would also cause considerable attenuation (i.e. scattering out of the beam). The absence of "absorption" in the hardened spectrum is an artifact due to the increase in high energy photons. The low energy flux remains about constant. In general, intensity changes across

the pulse can not be due to photoelectric absorption since the spectra never show low energy deficiencies.

All of the beaming mechanisms proposed thus far relate the beam directionality to magnetic field lines. In addition, a change in the viewing direction relative to the magnetic field lines (i.e. a change in pulse phase) alters the observed spectrum. This could be the cause of the observed spectral change. If the double-peaked pulse is initially considered to be a single broad feature, then the spectral hardening appears to be symmetrical with respect to it (see Figure 1). In other words, the pulse is narrower at higher energies (from 2 to 20 keV at least). A similar spectral hardening has been observed in the Cen X-3 pulse (Ulmer 1975, Swank 1976).

Models such as that of Basko and Sunyaev (1975) which predict spectral softening with narrowing beam, appear to be ruled out. They assume a surface magnetic field  $B \gtrsim 10^{12}$  gauss so that outgoing photons experience anisotropic Compton scattering. Tsuruta (1974) suggested that a similar mechanism could produce a pulse which narrows at higher energies. In this model the pulse shape is variable and the interpeak minimum is due to absorption by varying amounts of accreting matter. This observation shows no additional low energy absorption in the interpeak region and the stability of the pulse shape indicates either that the accretion rate does not change or that the pulse shape is not strongly dependent on this rate.

Cyclotron radiation in either a fan or pencil pattern produces a beam which narrows with increasing energy (Gnedin and Sunyaev 1973). A recent model of Tsygan (1976) in which the beam is formed by the accretion of a relativistic plasma onto the magnetic pole also predicts this behavior. In this model the field may only be as strong as  $3 \times 10^{10}$  gauss. Future observational tests could further narrow the acceptable models. Polarization measurements should distinguish between pencil and fan beams (Gnedin and Sunyaev 1973). A search for an emission "gyroline" (cf. Basko and Sunyaev 1975) at the cyclotron energy should be continued to determine whether a low field model is acceptable.

The region of spectral hardening extends over  $\sim 1/3$  of the double-peaked structure. This may indicate the intrinsic beam width. There is an intensity asymmetry relative to this intrinsic beam. It is interesting to note that the intensity deficiencies in the pulse--the interpeak and the pulse minimum regions--both occur later than and with  $\pi/2$  phase of the center of the hardened region. This could imply a stable region of scattering which reduces the intensities during these phases and which lags behind the intrinsic beam. We assume that a Thomson scattering region exists which distorts a symmetric pulse shape but not the spectrum. The optical depth with respect to Thomson scattering must be  $\lesssim 1$  to perform these functions. This is not atypical for the walls of accretion columns or the

shell at the Alfvén radius (Basko and Sunyaev 1976, McCray and Lamb 1976). The optical depth with phase and the "de-scattered" pulse are shown in Figure 3.

The Thomson scattering region is relatively thick at both ends and thin in the middle (Figure 3). This could correspond to a cross section of the accretion column. The leading edge is more prominent. The phase lag of the scatterer relative to the intrinsic beam could be due to a bend in the accretion column. Since the magnetic field strength decreases rapidly with distance ( $\propto R^{-3}$ ) and the corotation velocity increases ( $\propto R$ ) it is possible that the magnetic field lines and the accretion column bend in the direction opposite to the rotation. Near the surface this bending would be minimal so that the beaming would remain in the radial direction. At larger radii the bending increases and this results in the phase lag of the scattering region.

Basko and Sunyaev (1976b) have reported that many of the previously suggested beaming mechanisms fail when the X-ray luminosity,  $L_x \gtrsim 10^{37} (\frac{M}{M_\odot})$  erg/s. This is close to the Her X-1 luminosity. They suggest alternatively that the pulse modulation is due to material at the Alfvén surface which periodically shields part of the emitting region. Compton optical depths on the order of 1-3 in their model are sufficient to explain the modulation but not the detailed pulse structure. The present model explains the pulse structure by the shape of the scattering

accretion column. Since the Her X-1 pulse shape does not change, it is reasonable to assume that the scattering region is rigidly tied to the pulse formation region (hot spot). The accretion column fulfills this last requirement better than the material at the Alfvén surface, the distribution of which may be variable on short ( $\sim 5$  hr) time scales (Pravdo *et al.* 1977). McCray and Lamb (1976) speculate that the Alfvén shell is most dense at the magnetic equator and transparent at high magnetic latitudes except at the accretion columns. If this is the case, the scattering depth near the magnetic pole is likely to vary in a manner similar to the model depicted in Figure 3.

#### V. SUMMARY

A phenomenological model is proposed to explain the present observations of spectral variability with pulse phase. A region of spectral hardening which extends over less than one tenth of the pulse, is identified with an intrinsic beam. This beam is probably due to a varying view direction relative to the pulsar magnetic field. Other observational tests, as discussed in the text, are necessary to distinguish among the remaining viable pulse formation models.

The average Her X-1 pulse shape has remained approximately unchanged. The features discussed in this work have persisted in other observations. Since the intensity profile is asymmetric relative to the spectral profile, its properties may be independent of the mechanism which produces the intrinsic beam. A stable

region of varying Compton optical depth which lags behind the intrinsic beam can explain the intensity profile by modifications of a symmetric pulse. This scattering region could be the accretion column which is bent by the effects of rotation.

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#### FIGURE CAPTIONS

- Figure 1a. Energy-integrated (2-31 keV) pulse light curve.  
b. Spectral number index as a function of pulse phase.  
c. "Absorption" as a function of pulse phase. This is a useful parameter to observe spectral changes but is not to be interpreted as low-energy absorption.
- Figure 2. Spectra obtained from different pulse phases. The spectrum with the filled circles is taken from the center of the hardened region. The other spectrum comes from the interpeak region.
- Figure 3. Compton scattering optical depth as a function of pulse phase and the "descattered" pulse.





